GAMMA RAY PULSARS

Multiwavelength Observations

David J. Thompson

Laboratory for High Energy Astrophysics

NASA Goddard Space Flight Center

Greenbelt, Maryland 20771 USA

dji@egret.gsfc.nasa.gov

Abstract   High-energy gamma rays are a valuable tool for studying particle acceleration and radiation in the magnetospheres of energetic pulsars. The seven or more pulsars seen by instruments on the Compton Gamma Ray Observatory (CGRO) show that: the light curves usually have double-peak structures (suggesting a broad cone of emission); gamma rays are frequently the dominant component of the radiated power; and all the spectra show evidence of a high-energy turnover. For all the known gamma-ray pulsars, multiwavelength observations and theoretical models based on such observations offer the prospect of gaining a broad understanding of these rotating neutron stars. The Gamma-ray Large Area Space Telescope (GLAST), now in planning for a launch in 2006, will provide a major advance in sensitivity, energy range, and sky coverage.

Introduction

Pulsars are particularly interesting astrophysical objects because we know so much about them. Most of that information is derived from their timing properties. Measurement of the period P and period derivative $\dot{P}$ first identified pulsars as compact objects. Under fairly general assumptions that pulsars are rapidly-rotating neutron stars with a strong dipole magnetic field, a whole range of physical parameters can be estimated from these timing parameters. Examples include the timing age, the spin-down energy loss, the surface magnetic field, and the open field line voltage (Thompson, 2000).

1

Gamma-Ray Pulsar Multiwavelength Light Curves

The telescopes on the Compton Gamma Ray Observatory identified seven or more gamma-ray pulsars, some with very high confidence and others with less certainty. Figure 1 shows the light curves from the seven highest-confidence gamma-ray pulsars in five energy bands: radio, optical, soft X-ray (<1 keV), hard X-ray/soft gamma ray ($\sim$10 keV - 1 MeV), and hard gamma ray (above 100 MeV). Based on the detection of pulsations, all seven of these are positive detections in the gamma-ray band. The weakest (PSR B1951+32) has a statistical probability of occurring by chance of $\sim 10^{-9}$.

Some important features of these pulsar light curves are:

- They are not the same at all wavelengths. Some combination of the geometry and the emission mechanism is energy-dependent. In soft X-rays, for example, the emission in same cases appears to be thermal, probably from the surface of the neutron star; thermal emission is not the origin of radio or gamma radiation.

- Not all seven are seen at the highest energies. PSR B1509−58 (which has the strongest magnetic field among the gamma-ray pulsars) is seen up to 10 MeV by COMPTEL (Kuiper et al. 1999), but not above 100 MeV by EGRET.

- The six seen by EGRET all have a common feature - they show a double peak in their light curves. Because these high-energy gamma rays are associated with energetic particles, it seems likely that the particle acceleration and interactions are taking place along a large hollow cone or other surface. Models in which emission comes from both magnetic poles of the neutron star appear improbable in light of the prevalence of double pulses.

In addition to the six high-confidence pulsar detections above 100 MeV, at least three additional radio pulsars may have been seen by EGRET. Figure 2 shows their light curves in radio, optical, X-ray, and gamma rays. The gamma-ray light curves are shown without the zero suppression used in some of the original references. These three all have statistical probabilities in the 10^{-4} range, or about 5 orders of magnitude less convincing than the weakest of the seven on the previous figure. These are good candidates, but they are not strong enough to be used as discriminators between models.

Some features of these pulsars are:

- PSR B1046−58, which may be the counterpart of 3EG J1048−5840, has properties similar to Vela and PSR B1706−44 (Kaspi et al.

2000). It also has an associated X-ray source, but this source is not pulsed.

- PSR B0656+14 has timing properties similar to Geminga. It is a well-known X-ray pulsar, and optical pulsations have been seen. It is not detected in the EGRET catalog as a source by spatial analysis (Ramanamurthy et al. 1996).
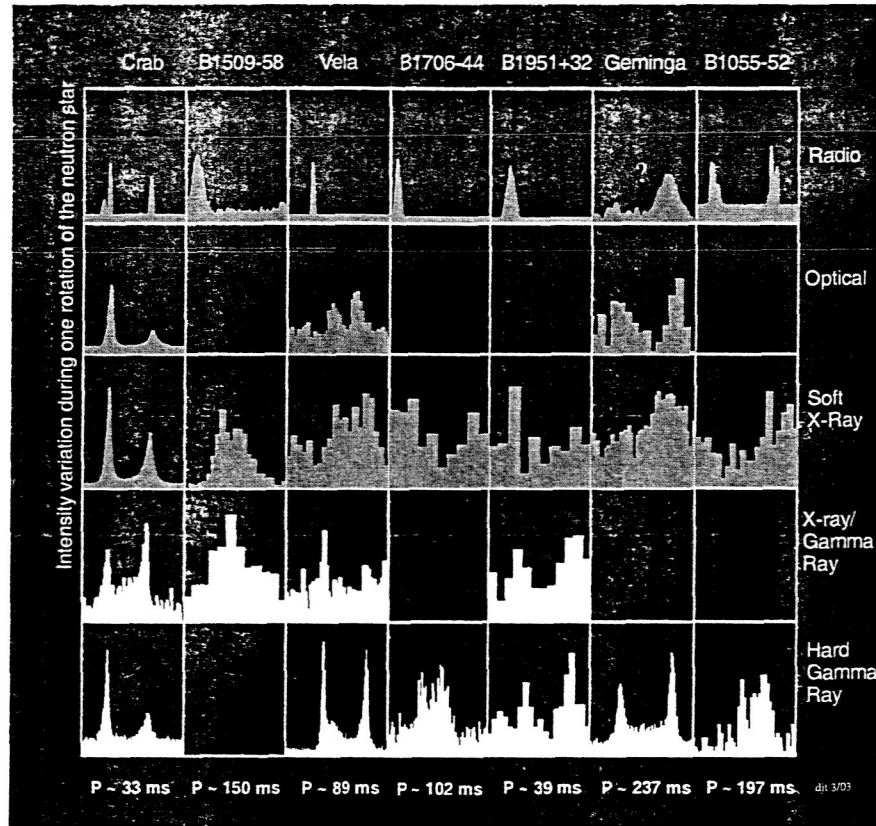

Figure 1. Light curves of seven gamma-ray pulsars in five energy bands, from left to right in order of characteristic age. Each panel shows one full rotation of the neutron star. The X-ray and gamma-ray references are those from Fig. 1 of Thompson (2001), with the addition of the X-ray data for PSR B1706−44 from Gotthelf, Halpern, and Dodson (2002). Radio references (left to right): Manchester, 1971; Ulmer et al., 1993; Kanbach et al., 1994; Johnston et al., 1992; Kulkarni et al., 1988, Kuz'min and Losovsky, 1997; Fierro et al., 1993. Optical references: Crab, Groth, 1975; Vela, Manchester et al., 1980; Geminga, Shearer et al., 1998.

4

- PSR J0218+4232 is the only millisecond pulsar with evidence of
  gamma-ray emission (Kuiper et al. 2000, 2002). The observed
  gamma-ray pulse resembles that seen in X-rays. Spatial analysis
  of this gamma-ray source is complicated by the presence of 3C66A,
  a BL Lac object about 1 degree away from the pulsar on the sky
  (Hartman et al. 1999).

A note on gamma-ray pulsar variability: although the pulsations
themselves are a periodic variability with very high contrast between
peaks and valleys, no strong evidence has been found for longer-term
variability of the gamma-ray emission from pulsars, in contrast to many
other gamma-ray sources (e.g. McLaughlin et al. 1996, Torres et al.
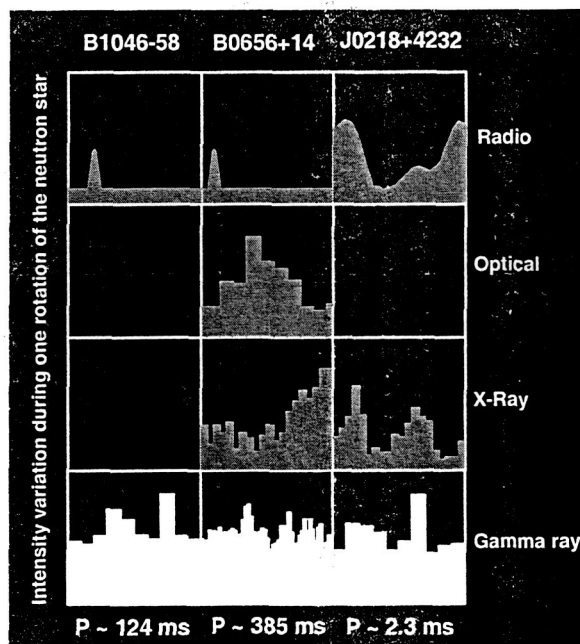2001, Nolan et al., 2003).

Figure 2. Light curves of three candidate gamma-ray pulsars. Each panel shows
one full rotation of the neutron star. References: PSR B1046-58: (Kaspi et al. 2000);
PSR B0656+14: (radio: Kuz'min et al. 1998; optical: Shearer et al. 1997; X-ray:
Finley 1994, gamma-ray: Ramanamurthy et al. 1996); PSR J0218+4232 (Kuiper et
al. 2000, 2002).

Gamma-Ray Pulsar Multiwavelength Energy Spectra

While the pulsations identify sources as rotating neutron stars, the observed energy spectra reflect the physical mechanisms that accelerate
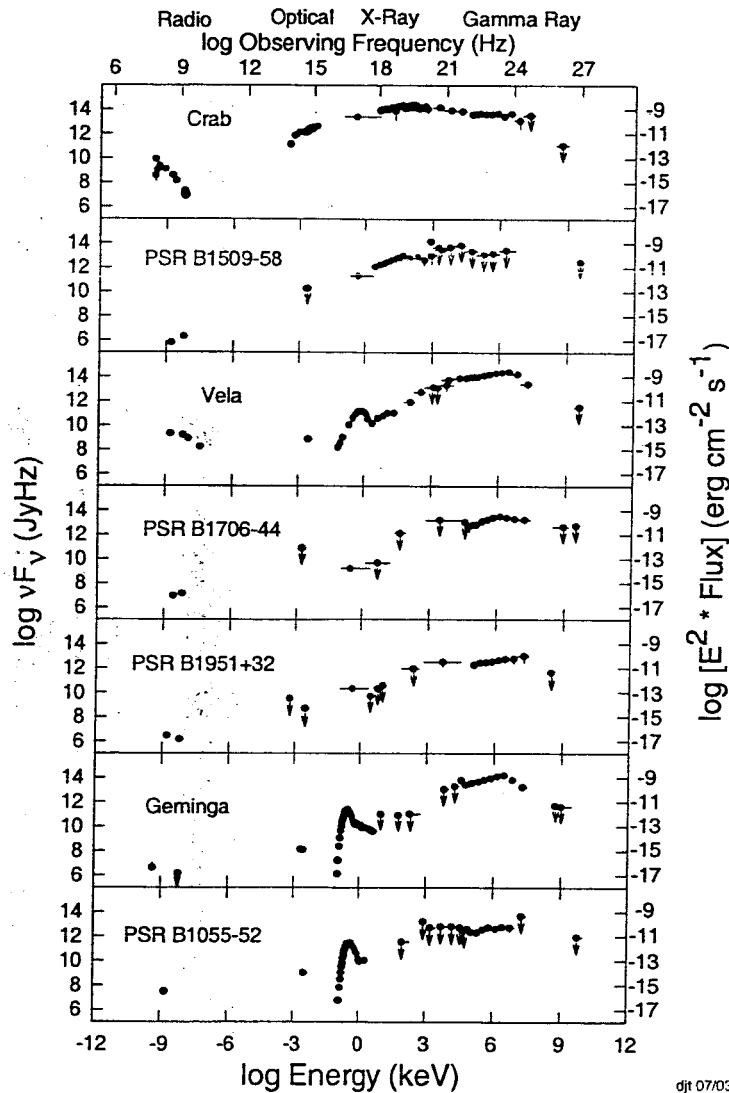

Figure 3. Multiwavelength spectra of seven gamma-ray pulsars. Updated from Thompson et al. (1998) with data from Fierro et al. (1998) for the Crab (gamma rays) and Jackson et al. 2002 for Geminga (hard X-rays).

charged particles and help identify interaction processes that produce
the pulsed radiation. Broadband spectra for the seven highest-confidence
gamma-ray pulsars are shown in Fig. 3. The presentation in $\nu F\nu$ format
(or E^2 times the photon number spectrum) indicates the observed power
per frequency interval across the spectrum. In all cases, the maximum
power output is the in the gamma-ray band. Other noteworthy features
on this figure are:

- The distinction between the radio emission (which originates from
  a coherent process) and the high-energy emission (probably from
  individual charged particles in an incoherent process) is visible for
  some of these pulsars, particularly Crab and Vela.

- Vela, Geminga, and B1055−52 all show evidence of a thermal com-
  ponent in X-rays, thought to be from the hot neutron star surface.

- The gamma-ray spectra of known pulsars are typically flat, with
  most having photon power-law indices of about 2 or less. Energy
  breaks are seen in the 1-4 GeV band for several of these pulsars.
  These changes in spectral index appear to be related to the cal-
  culated surface magnetic field of the pulsar, as shown in Fig. 4.
  The lowest-field pulsars have no visible break in the EGRET en-
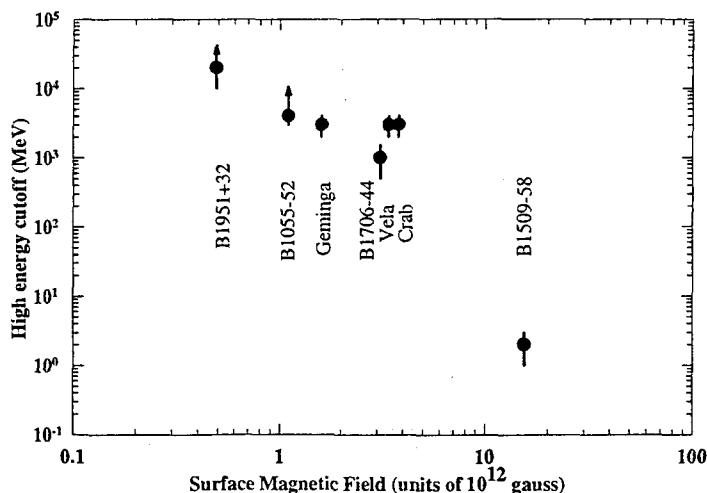

Figure 4. High-energy cutoff energy for gamma-ray pulsars as a function of surface
magnetic field. For PSRs B1951+32 and B1055−52, only a lower limit to the cutoff
energy can be determined from the EGRET data.

ergy range; the existence of a spectral change is deduced from the absence of TeV detections of pulsed emission. The highest-field pulsar among these, B1509−58, is seen only up to the COMPTEL energy band.

- No pulsed emission is seen above 30 GeV, the upper limit of the Compton Observatory/EGRET observations. The nature of the high-energy cutoff is an important feature of pulsar models.

- Although Fig. 3 shows a single spectrum for each pulsar, the pulsed energy spectrum varies with pulsar phase. A study of the EGRET data by Fierro et al. (1998) of the phase-resolved emission of the three brightest gamma-ray pulsars (Vela, Geminga, Crab) showed no simple pattern of variation of the spectrum with phase that applied to all three pulsars. A broadband study of the Crab by Kuiper et al. (2001) indicated the presence of multiple emission components, including one that peaks in the 0.1 - 1 MeV range for the bridge emission between the two peaks in the light curve. Improved measurements and modeling of the phase-resolved spectra of pulsars can be expected to be a powerful tool for study of the emission processes.

The measured spectra can be integrated to determine the energy flux of each pulsar. Except for the Crab and PSR B1509−58, whose luminosity peaks lie in the ∼100 KeV - 1 MeV range, the energy flux for the other gamma-ray pulsars is dominated by the emission above 10 MeV. Even then some interpolation or extrapolation may be needed for some pulsars that do not have spectra measured over a broad energy band; therefore these flux values have significant uncertainty. The energy flux can be converted to an estimated luminosity by using the measured distance to the pulsar and an assumed emission solid angle. For simplicity, I assume an emission into one steradian. This value is unlikely to be the same for all pulsars but provides a simple reference point for comparison. A significant uncertainty in such calculations is introduced by the distance estimate. Only for the nearby Geminga, B0656+14, and Vela pulsars is the distance well determined by parallax measurements (Brisken et al., 2002, 2003; Caraveo et al., 1996, 2001). Analysis of other distances based on the radio Dispersion Measure is less certain and is dependent on a model of the Galactic electron density. The distances given here reflect the new NE2001 electron density model of Cordes and Lazio (2002). In particular, this new model finds that B1055−52 and J0218+4232 are substantially closer than previous models. Table 1 summarizes these results for the ten pulsars.

Table 1. Summary Properties of the Highest-Confidence and Candidate Gamma-Ray Pulsars

Name	P (s)	τ (Ky)	$\dot{E}$ (erg/s)	F_E (erg/cm^{2}s)	d (kpc)	L_{HE} (erg/s)	η (E>1 eV)
Crab	0.033	1.3	4.5×10^{38}	1.3×10^{-8}	2.0	5.0×10^{35}	0.001
B1509$-$58	0.150	1.5	1.8×10^{37}	8.8×10^{-10}	4.4	1.6×10^{35}	0.009
Vela	0.089	11	7.0×10^{36}	9.9×10^{-9}	0.3	8.6×10^{33}	0.001
B1706$-$44	0.102	17	3.4×10^{36}	1.3×10^{-9}	2.3	6.6×10^{34}	0.019
B1951+32	0.040	110	3.7×10^{36}	4.3×10^{-10}	2.5	2.5×10^{34}	0.007
Geminga	0.237	340	3.3×10^{34}	3.9×10^{-9}	0.16	9.6×10^{32}	0.029
B1055$-$52	0.197	530	3.0×10^{34}	2.9×10^{-10}	0.72	1.4×10^{33}	0.048
B1046$-$58	0.124	20	2.0×10^{36}	3.7×10^{-10}	2.7	2.6×10^{34}	0.013
B0656+14	0.385	100	4.0×10^{34}	1.6×10^{-10}	0.3	1.3×10^{32}	0.003
J0218+4232	0.002	460,000	2.5×10^{35}	9.1×10^{-11}	2.7	6.4×10^{33}	0.026

Other Candidate Isolated Neutron Stars

Several sources seen in gamma rays have characteristics that strongly resemble those of the known gamma-ray pulsars, but without evidence of gamma-ray pulsation. Examples are:

- 3EG J1835+5918/RX J1836.2+5925 is a likely Isolated Neutron Star (INS) similar to Geminga, based on multiwavelength observations (Mirabal et al. 2001, Reimer et al., 2001; Halpern and Mirabal 2001; Halpern et al. 2002) that show an X-ray source with both a thermal and nonthermal component, a gamma-ray source with no variability, a hard spectrum and high-energy cutoff, and no prominent optical or radio counterpart. No pulsations have yet been found at any wavelength.

- PSR J2229+6114 is a young radio and X-ray pulsar with a high spindown rate, found in an EGRET source error box (Halpern et al., 2001). Analysis of its energetics makes it a plausible counterpart for the gamma-ray source. A search for pulsations in the gamma-ray data was inconclusive (Thompson et al., 2001).

- 3EG J2020+4017 (Brazier et al, 1996) and 3EG J0010+7309 (Brazier et al., 1998) are positionally associated with supernova remnants γ-Cygni and CTA1, respectively. The gamma-ray sources may have X-ray counterparts, are non-variable, and have flat spectra similar to other gamma-ray pulsars. No pulsations have been seen from these sources, however.

- A number of other young radio pulsars have been found in EGRET error boxes (Camilo et al. 2001; D'Amico et al. 2001; Torres, Butt and Camilo 2001). The search for radio pulsars in EGRET error boxes is an ongoing effort, particularly using the large number of new pulsars being found with the Parkes survey (Kramer et al., 2003).

Some, perhaps many, of these objects are likely to be gamma-ray pulsars. In light of the relatively large gamma-ray error boxes and the absence of any gamma-ray pulsations, however, I take the conservative approach of including only the ten sources with at least some evidence of pulsed gamma rays in further discussions.

Gamma-Ray Pulsars Compared to the General Pulsar Population

The sample of ten gamma-ray pulsars, using both the established and candidate sources, can be compared to other pulsars in terms some of the derived physical parameters. Figure 5 is a distribution of pulsars as a function of their period and period derivative, derived from the new ATNF Pulsar Catalogue (http://www.atnf.csiro.au/research/pulsar/psrcat/). The gamma-ray pulsars are shown as squares. Also shown are some of the derived physical parameters. The gamma-ray pulsars tend to be concentrated (with the exception of the one millisecond candidate) in a region with high magnetic field (but not magnetar-strength) - shown by the dashed lines, and relatively young ages - shown by the solid lines. All ten gamma-ray pulsars share a third characteristic, shown by the dotted line, of having the open field line voltage high compared to most pulsars. This is not surprising, since the particles are being accelerated electromagnetically.

The open field line voltage, which is also proportional to the polar cap (Goldreich-Julian) current, has long been recognized as a significant parameter for gamma-ray pulsars (Arons, 1996). Figure 6 illustrates that the pulsar high-energy luminosities, integrated above 1 eV, are approximately proportional to this parameter, shown by the solid line in the figure. An interesting question is what happens for lower voltages, where the high-energy luminosity converges with the total spin-down energy available, shown by the dashed line. This will be a question for future missions.

Pulsars at the Highest Energies

What happens to pulsars at the highest energies? No pulsars have been seen at TeV energies. The upper end of the EGRET range rep-

resents the highest energies for detections of pulsed emission. Figure 7
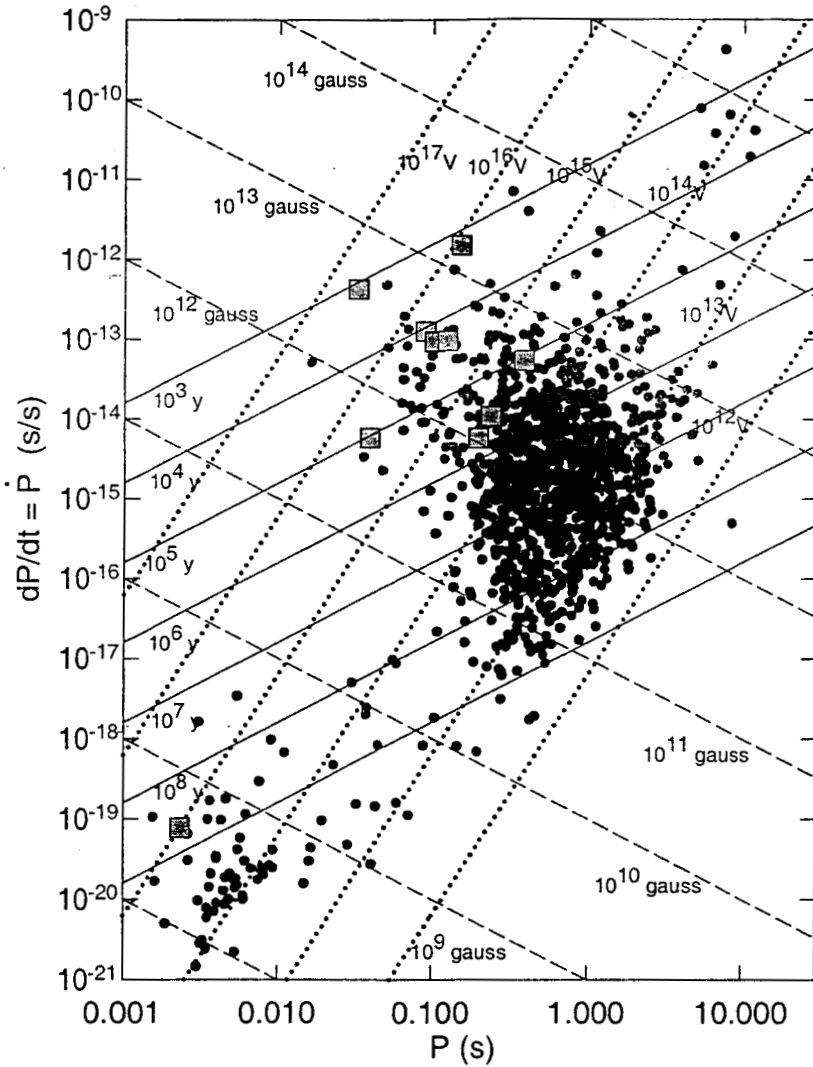

Figure 5. Period v. period derivative for the ATNF Catalogue of Pulsars (http://www.atnf.csiro.au/research/pulsar/psrcat/). Small dots: no gamma-ray emission. Large dark boxes: seven high-confidence gamma-ray pulsars. Large light boxes: three lower-confidence gamma-ray pulsars. Solid lines: timing age. Dotted line: open field line voltage. Dashed line: surface magnetic fields.

shows the light curves for six EGRET pulsars. Despite the very limited statistics, several features of these pulsars are visible:

- There is clear evidence for pulsed emission above 5 GeV for the Crab, Vela, Geminga, and B1706−44 pulsars, and the other two are consistent with having pulsed emission.

- In all cases, one of the two pulses seen at lower gamma-ray energies has faded at these high energies, leaving the other pulse dominant. For all except PSR B1706−44, it is the trailing pulse that dominates (B1951+32 has pulses so close to 180° apart that determining the leading pulse is not clear).

- Except for the Crab, the emission from the other pulsars is concentrated strongly within the pulse as defined by the lower-energy gamma rays. The extended emission from the Crab is thought to be unpulsed emission from the supernova remnant.
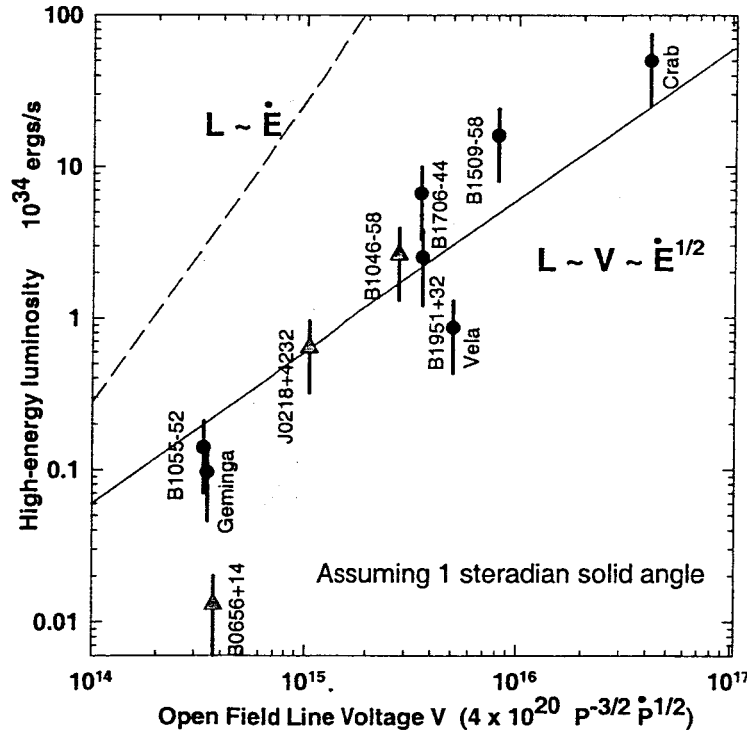

Figure 6. High-energy pulsar luminosity as a function of the open field line voltage. Circles: high-confidence pulsars; Triangles: lower-confidence pulsars.

- The one pulse seen for the Crab appears to be displaced from the pulse seen at lower energies, a feature noted also by Kuiper et al. (2001), possibly a continuation of the narrowing of the gap
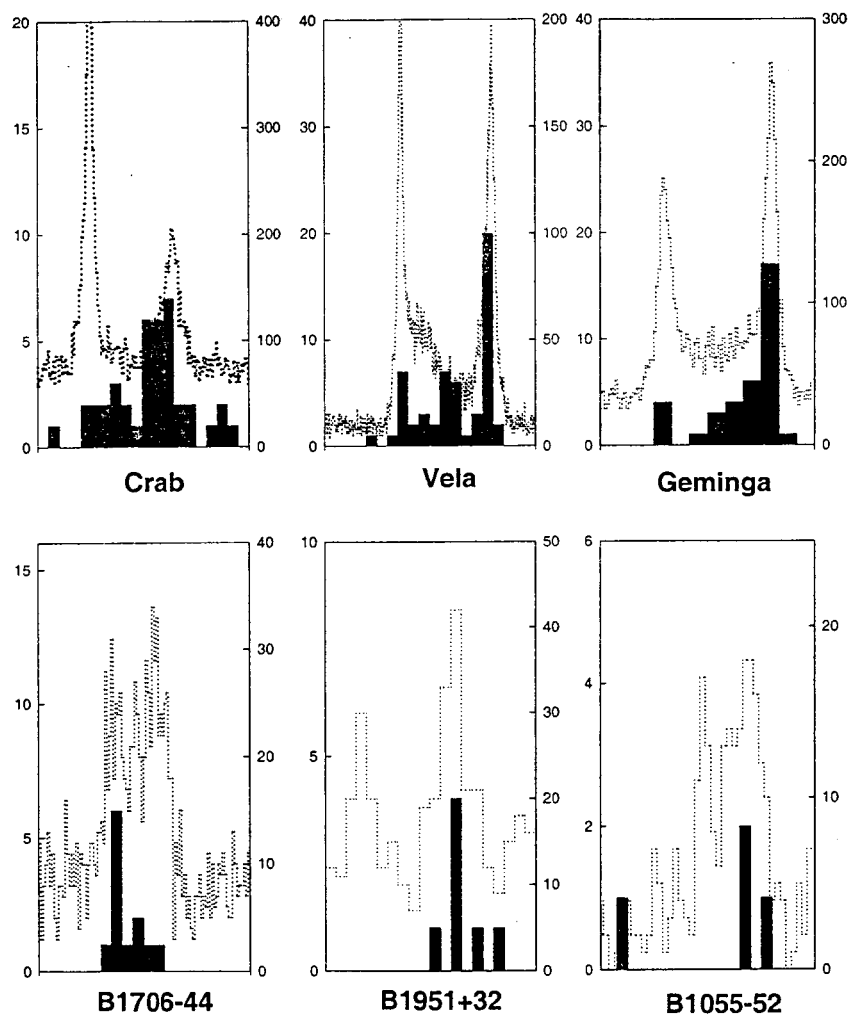

Figure 7. Light curves of six gamma-ray pulsars above 100 MeV (dotted lines, right-hand scale) and above 5 GeV (dark histogram, left-hand scale). Each panel shows one full rotation of the neutron star.

between the two pulses that extends from the infrared to gamma-ray energies (Eikenberry and Fazio, 1997; Ramanamurthy, 1994).

The gap between about 10 GeV (where EGRET runs out of photons) and the current generation of ground-based telescopes is very important. It is hard to predict from the limited EGRET data what is expected even at 100 GeV. Figure 6 shows the spectrum of Vela, the brightest of the EGRET pulsars. This spectrum is shown in $\nu F \nu$ or power per logarithmic energy interval format. The 10-30 GeV point is based on only 4 photons, and the absolute calibration of EGRET at these energies is fairly uncertain. Also shown are the spectra expected in two popular gamma-ray pulsar models, the polar cap (Daugherty and Harding 1996; Harding 2000) and the outer gap (Romani, 1996, 2000). The large error bars on the EGRET data make them consistent with both models. The extrapolation to higher energies is, however, dramatically different. There is also the possibility of a second, inverse-Compton component of the pulsed radiation at higher energies, expected in some outer gap models (Romani, 1996), although there is yet no observational evidence for that component. Searching for that second component will be an important goal of the next generation of very-high-energy gamma-ray telescopes.
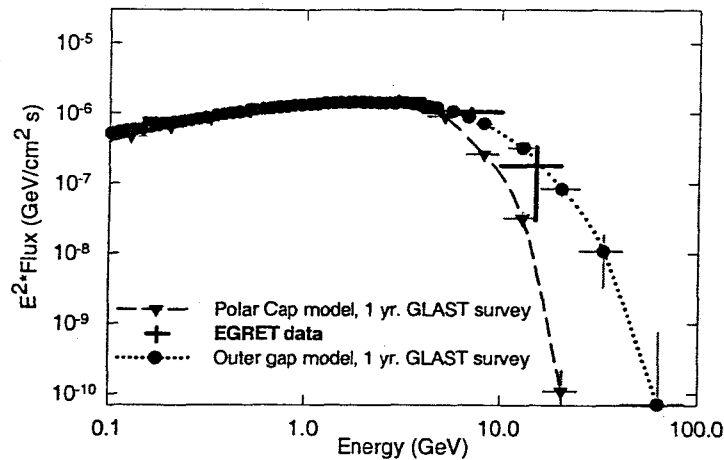

Figure 8. High-energy spectrum of the Vela pulsar. Heavy error bars: EGRET data (Kanbach et al. 1994). Circles and dotted line: Outer gap model (Romani, 1996, 2000). Triangles and dashed line: Polar cap model (Daugherty and Harding 1996; Harding 2000). Error bars shown on the models are those expected from the GLAST mission (Gehrels and Michelson, 1999) in a one-year sky survey.

Future Pulsar Observations at High Energies

The high luminosity in the GeV energy range and the drop-off above that part of the spectrum suggest that the GLAST Large Area Telescope (LAT) will be the next big step in gamma-ray pulsar observations. The Italian AGILE mission will certainly make a contribution, especially in confirming those candidate pulsars for which the EGRET data are marginal, but GLAST LAT will be needed for a major increase
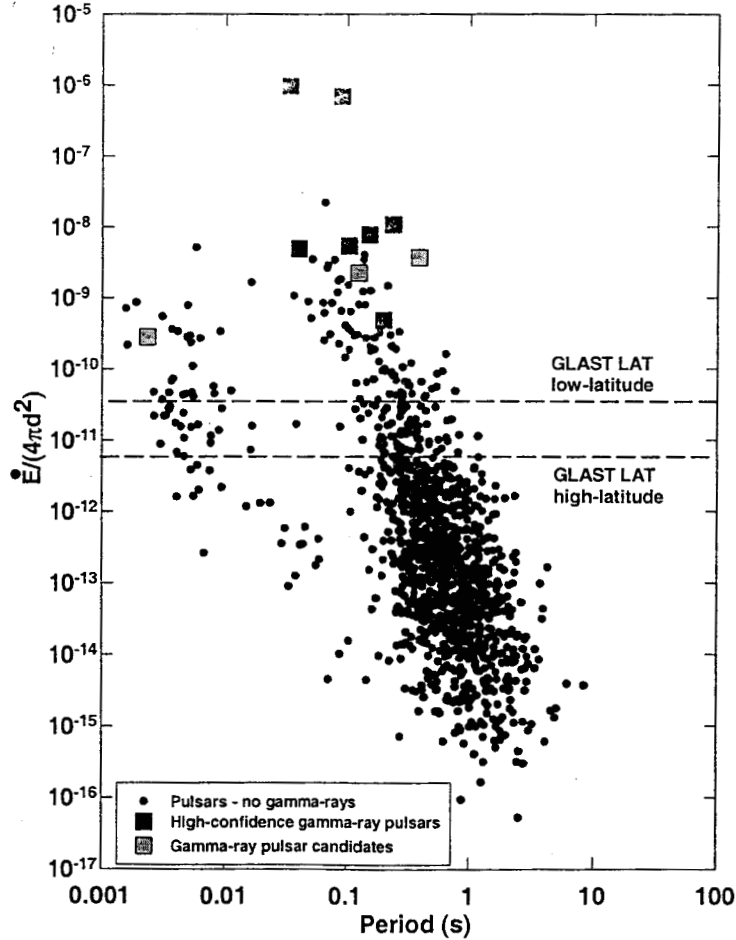

Figure 9. Gamma-ray pulsar observability, as measured by the spin-down energy seen at earth.

in sensitivity and energy reach. Figure 8 shows one of the ways that GLAST will help - the smaller error bars on the theoretical curves show two models' predictions folded through the GLAST LAT sensitivity for a one-year sky survey. GLAST LAT will easily distinguish spectra such as these and might detect a second component at higher energies. A second strength of GLAST LAT will be in its much higher sensitivity than previous instruments. Figure 9 shows one of the classic measures of pulsar observability: the pulsar spin-down luminosity divided by 4π times the square of the distance, the total available pulsar energy output at Earth. The 10 gamma-ray pulsars and candidates are shown as the large squares. Six of the seven pulsars with the highest value of this parameter are gamma-ray pulsars. Below these, only a handful of pulsars are visible in gamma rays. The GLAST LAT sensitivity will push the lower limit down substantially farther. Two sensitivity limits are shown for GLAST LAT - one for low-Galactic-latitude sources and one for those at high latitudes, because the high diffuse emission along the Galactic plane reduces the sensitivity for point source detection. The phase space that GLAST LAT opens up is substantial.

How many pulsars will GLAST LAT see? To some extent that number depends on which model best describes the emission and how the pulsars are distributed on the sky. One empirical estimate can be made by constructing a logN-logS curve from the known pulsars. Figure 10 uses all nine of the high-energy gamma-ray pulsars to construct this function. The simple linear fit suggests that GLAST might expect to detect between 30 and 100 gamma-ray pulsars. The range of sensitivity is dependent on where the pulsars lie with respect to the Galactic plane. In some respects this figure is pessimistic, possibly due to the small sample. A disk population should increase linearly with decreasing sensitivity, but the fitted line goes as the -0.5 power of the sensitivity. A linear function would raise the number of pulsars to more than 100. Other methods have given even larger numbers of potential pulsar detections (e.g. McLaughlin and Cordes, 2000).

Just as interesting as the number of pulsars to be seen by GLAST is which particular pulsars will be seen. Such observations are probably the best discriminator among models. Table 2 is a compilation with help from the theorists involved, showing the expected flux for various radio pulsars that have not yet been seen in gamma rays. In some case, the predicted flux values exceed the limits seen with EGRET, indicating a limitation of the models. For many of these pulsars, different models make predictions that differ by more than an order of magnitude. In these units, the GLAST LAT sensitivity is 2 for pulsars near the plane and 0.2 for high-latitude pulsars; therefore GLAST LAT will certainly

provide solid observational tests of these and other gamma-ray pulsar models.

The third, and perhaps most important, capability of GLAST LAT for pulsars will be its ability to find unknown pulse periods, in order to look for more Geminga-like pulsars. Various analyses have shown that only the brightest pulsars could be found in the EGRET data without independent information (Brazier and Kanbach 1996; Jones, 1998; Chandler et al. 2001). For all of the other unidentified EGRET sources, the photons are just too few and too far apart in time to derive unambiguous pulse periods. With GLAST LAT, periodicity searches will be feasible for most, if not all, the unidentified EGRET sources (Mattox, 2000; McLaughlin and Cordes, 2000). The potential is to find a whole new population of rotation-powered pulsars, much as X-ray astronomy has started to do in the past few years. This could be an important
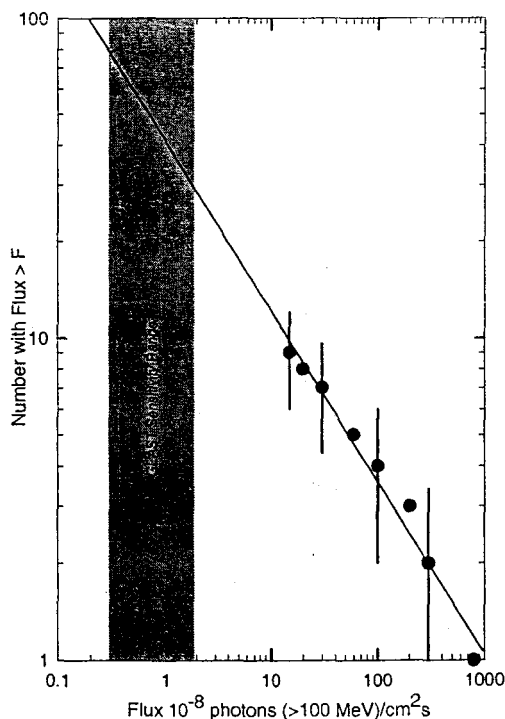

Figure 10. Cumulative number of gamma-ray pulsars seen by EGRET as a function of observed flux. Error bars are statistical and are shown on alternating data points for clarity.

Table 2. Predicted gamma-ray fluxes (units of 10^{-8} ph [E> 100 MeV] cm^{-2}s^{-1})

Pulsar J	Zhang & Harding (2000)	Rudak &Dyks (1998)	Romani (2000)	Cheng &Zhang (1998)
1932+1059	<580[a]	90	~0	<16
0953+0755	<500[a]	90	~0[b]	<16
0437−4715	<230[a]	<2	~0	<16
2043+2740	50	30	~0[b]	50
1826−1334	20	20	≤1	<16
1803−2137	20	20	30	<16
0742−2822	20	20	≤7	25
0117+5914	20	20	≤35	20
1801−2451	15	10	23	<16
1908+0734	50	10	~0	<16
1730−3350	10	10	≤20	<16
0538+2817	15	10	≤24	20
0358+5413	10	8	≤9	16
1453−6151	10	<2	~0[b]	20
2337+6151	8	<2	≤11	20
1824−2452	16	<2	≤9	<16
1637−4553	4	<2	≤7	<16

[a] Upper limit because the predicted emission is a large fraction of the pulsar spin-down luminosity.
[a] Small flux predicted due to beaming.

new window onto the physics of the extreme conditions around these spinning neutron stars.

Summary

- Gamma-ray pulsars are multiwavelength objects that provide a valuable probe of particle acceleration and interaction in the extreme conditions found near rotating neutron stars.

- At least 7 pulsars are seen in gamma rays (six of those at energies above 100 MeV), with 3 or more additional good candidates and some other likely isolated neutron stars that have not yet shown evidence of pulsation.

- The gamma-ray light curves generally differ from those at lower energies. The double-pulse structure indicates emission above a single magnetic pole. Above 5 GeV, the known gamma-ray pulsars show only one prominent peak in their light curves.

- The broadband energy spectra of these pulsars show multiple components. The maximum power per frequency interval is found in

the gamma-ray band, and all these pulsars show a high-energy cutoff, possibly related to the surface magnetic field strength.

- Compared to the general pulsar popultion, gamma-ray pulsars tend to be younger, have higher magnetic fields, and have higher open field line voltages. The gamma-ray pulsar luminosities seem to increase with open field line voltage or particle current.

- The changing shape of the light curves and energy spectra in the 1-20 GeV range make this band particularly interesting for future observations.

- GLAST, along with other satellite and ground-based gamma-ray telescopes, will make a major advance in gamma-ray pulsar studies. Of particular interest for testing pulsar models will be learning which radio pulsars are gamma-ray bright, since different models make substantially different predictions.

References

Arons, J., *A&AS* **120**, 49-60 (1996).

Brazier, K.T.S. et al., *MNRAS* **281**, 1033-1037 (1996).

Brazier, K.T.S., Reimer, O., Kanbach, G., Carrimañana, A., *MNRAS* **295**, 819-824 (1998).

Brazier, K.T.S. and Kanbach, G., *A&AS* **120**, 85-87 (1996).

Brisken, Walter F., Benson, John M., Goss, W. M., Thorsett, S. E., *ApJ* **571**, 906-917 (2002).

Brisken, Walter F., Thorsett, S. E., Golden, A., Goss, W. M., *ApJ, submitted,* astro-ph/0306232 (2003).

Caraveo, P. A., De Luca, A., Mignani, R. P., Bignami, G. F., *ApJ* **561**, 930-937 (2001).

Caraveo, Patrizia A., Bignami, Giovanni F., Mignani, Roberto, Taff, Laurence G., *ApJ* **461**, L91-L94 (1996).

Chandler, A. M. et al., *ApJ* **556**, 59-69 (2001).

Cheng, K.S. and Zhang, L., *ApJ* **498**, 327-341 (1998).

Daugherty, J. K. and Harding, A. K.,*ApJ* **458** , 278-292 (1996).

Eikenberry, Stephen S., Fazio, Giovanni G., *ApJ* **476**, 281-290 (1997).

Fierro, J. M., Michelson, P. F., Nolan, P. L., Thompson, D. J., *ApJ* **494**, 734-746 (1998).

Finley, J.P., in: *The Soft X-Ray Cosmos*, ed. R. Petre, E.M. Schlegel, New York: AIP, AIP Conf. Proc. 313, 41-50 (1994).

Gehrels, N. and Michelson, P., *Astroparticle Phys.* **11**, 277-282 (1999).

Gotthelf, E. V., Halpern, J. P., Dodson, R., *ApJ* **567**, L125-L128 (2002).

Halpern, J. P. et al., *ApJ* **552**, L125-L128 (2001).

Halpern, J.P., Gotthelf, E.V., Mirabal, N., Camilo, F., *ApJ* **573**, L41-L44 (2002).

Halpern, J.P. and Mirabal, N., *ApJ* **547**, L137-L140 (2001).

Harding, A.K, private communication (2000).

Hartman, R. C. et al., *ApJS* **123**, 79-202 (1999).

Jackson, M. S., Halpern, J. P., Gotthelf, E. V., Mattox, J. R., *ApJ* **578**, 935-942 (2002).

Jones, B.B., PhD Thesis, Stanford University (1998).

Kanbach, G. et al., *A&A* **289**, 855-870 (1994).

Kaspi, V.M. et al., *ApJ* **528**, 445-453 (2000).

Kramer, M. et al., *MNRAS* **342**, 1299-1324 (2003).

Kuiper, L. et al., *A&A,* **351**, 119-132 (1999).

Kuiper, L. et al., *A&A* **359**, 615-626 (2000).

Kuiper, L., et al., *A&A* **378**, 918-935 (2001)

Kuiper, L., Hermsen, W., Verbunt, F., Ord, S., Stairs, I., Lyne, A., *ApJ* **577**, 917-922 (2002).

Kuz'min, A. D. et al., *A&AS* **127**, 355-366 (1998).

Kuz'min, A. D., Losovskii, B. Ya., *Astronomy Letters*, **23** 283-285 (1997).

Mattox, J.R., private communication (2000).

McLaughlin, M. A., Mattox, J. R., Cordes, J. M., Thompson, D. J., *ApJ* **473**, 763-772 (1996).

McLaughlin, M. A., Cordes, J. M., *ApJ* **538**, 818-830 (2000).

Mirabal, N., Halpern, J.P., Eracleous, M., Becker, R.H., *ApJ* **541**, 180-193 (2001).

Nolan, P. L. et al., *ApJ* in press (2003).

Ramanamurthy, P. V., *A&A* **284**, L13-L15 (1994).

Ramanamurthy, P.V. et al., *ApJ* **458**, 755-760 (1996).

Reimer, O., et al., *MNRAS* **324**, 772-780 (2001).

Romani, R.W., *ApJ* **470**, 469-478 (1996).

Romani, R.W., private communication (2000).

Rudak, B., and Dyks, J., *MNRAS* **295**, 337-343 (1998).

Thompson, D. J., in *High Energy Gamma-Ray Astronomy*, American Institute of Physics (AIP) Proceedings, **558**, Edited by Felix A. Aharonian and Heinz J. Vlk. American Institute of Physics, Melville, New York, p.103-114 (2001).

Thompson, D.J., *Adv. Space Res.* **25**, 659-668 (2000).

Thompson, D.J. et al., *ApJ* **516**, 297-306 (1999).

Torres, D. F., Romero, G. E., Combi, J. A., Benaglia, P., Andernach, H., Punsly, B., *A&A* **370**, 468-478 (2001).

Torres, Diego F., Butt, Yousaf M., Camilo, Fernando, *ApJ* **560**, L155-L158 (2001).

Torres, Diego F., Nuza, Sebastin E., *ApJ* **583**, L25-L29 (2003).

Zhang, B. and Harding, A.K., *ApJ* **532**, 1150-1171 (2000).